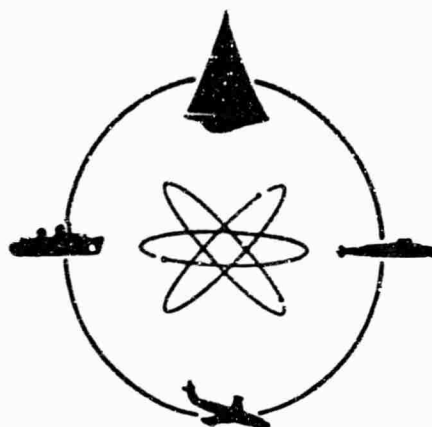# DAVIDSON LABORATORY

Report SIT-DL-69-1437

December 1969

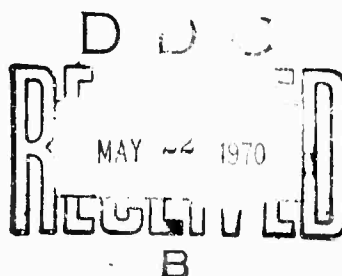## ENGINEERING APPROXIMATION OF MAXIMUM ACCELERATIONS EXPERIENCED BY PLANING CRAFT IN ROUGH WATER

by

John K. Roper

STEVENS INSTITUTE
OF TECHNOLOGY

CASTLE POINT STATION
HOBOKEN, NEW JERSEY

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DAVIDSON LABORATORY

Stevens Institute of Technology
Castle Point Station
Hoboken, New Jersey 07030

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EXPERIENCED BY PLANING CRAFT IN ROUGH WATER

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Approved

Daniel Savitsky

13 + viii pages   Daniel Savitsky
plus 4 tables, 10 figures   Assistant Director

ABSTRACT

An engineering procedure is presented for estimating the maximum impact accelerations experienced by planing craft in irregular head seas. General agreement between calculated and model test results indicates that the proposed method is realistic. The procedure should be particularly useful during preliminary design.

Keywords

CONTENTS

NOMENCLATURE

a	Horizontal distance from LCG
b	Beam
Cl_o	Total lift coefficient, zero deadrise $= f(Cl_\beta, \beta)$
Cl_{o_D}	Dynamic lift coefficient, zero deadrise $= .012\tau_o^{1.1}\lambda_o^{1/2}$
Cl_β	Total lift coefficient, deadrise surface $= \Delta/qb^2$
Cl_{β_D}	Dynamic lift coefficient, deadrise surface $= f(Cl_{o_D}, \beta)$
C_v	Speed coefficient $= \dot{x}/\sqrt{gb}$
g	Acceleration due to gravity
H_w	Wave height
$\dot{h}$	Wave particle velocity, vertical, at surface
i	Mass moment of inertia
L	Total lift
L_B	Buoyant lift
L_D	Dynamic lift
LCF	Centroid of chine planform area forward of transom
LCG	Center of gravity location forward of transom
ℓ	Effective wetted length
ℓ_c	Projected chine length
ℓ_w	Wave length
M	Applied moment
n	Incremental load factor
q	Dynamic pressure $= \dot{x}^2(\rho/2)$
T_w	Wave period
V	Speed, knots
$\dot{x}$	Horizontal velocity
$\dot{y}$	Vertical velocity

$\ddot{y}$ Vertical acceleration

$\dot{z}$ Velocity, relative to adjacent fluid, of planing body normal to its keel

β Deadrise angle

Δ Gross weight

$\ddot{\theta}$ Angular acceleration

λ Effective wetted length to beam ratio

ρ Mass density

τ Trim angle

ϕ Wave slope (maximum)

Subscripts

o   Denotes smooth water operation

max   Denotes rough water operation

CG   Denotes center of gravity

θ Denotes angular motion

INTRODUCTION

Research in the area of hydrodynamic impact has been carried out
mainly by the aerodynamicist in his studies of landings of water-based
aircraft and recently by the hydrodynamicist in his studies of ship
slamming. Numerous theoretical developments have been published and
a great deal of experimental data on hydrodynamic impact exists in
the various publications associated with these two technological
disciplines. A brief study was undertaken to review the existing
information on hydrodynamic impact and to exact therefrom those
results particularly applicable to the design of high speed planing
craft. In the course of this review, an empirical procedure was
formulated which allowed for reliable engineering estimates of the
maximum impact accelerations experienced by planing craft in rough
water. It was believed that this procedure would be of immediate
direct benefit to the small craft designer and, consequently, the
emphasis of the present report is on a description of this engineering
procedure and includes a comparison of computed and measured rough
water accelerations obtained in model tests at the Davidson Laboratory.

The present study was carried out under sponsorship of the Naval
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NRC62-419/9-18-68 (Code 438).

BACKGROUND

Some of the earliest studies of the phenomenon of hydrodynamic
Impact were initiated by aircraft designers concerned with the determin-
ations of hull impact loads for seaplanes alighting upon a smooth water
surface. Analytical and experimental investigations of hydrodynamic
impact were continuously pursued during the period when seaplanes were
a viable component of aviation. As a consequence, an extensive technical
literature was developed which is generally available in NACA (now NASA)
reports.

For the most part, seaplane impact theories deal mainly with the
case of constant deadrise surfaces alighting upon a smooth water surface
at a fixed trim angle such that the initial contact between hull and
water is at the transom-keel intersection and the maximum impact load
occurs prior to chine immersion. These conditions are typically repre-
sentative of most seaplane landings. Well-documented reviews of seaplane

Impact theory have been prepared by Mayo[1] and Monoghan[2]. In essence, these papers describe the impact process as the transfer of momentum from an impacting hull to an "added mass" of water which is directly associated with the hull during its contact with the water and to the "added mass" shed into the wake as the hull moves forward. The expression for the time rate of change of momentum between hull and added mass components then describes the differential equation of motion governing the impact. It is apparent then that this impact theory is dependent upon a proper definition of the form of added mass and, as a result, a substantial research effort has been directed to this end (von Karman[3], Wagner[4], Pabst[5], Milwitzky[6] among others). The added mass is defined for two-dimensional sections normal to the keel which are then integrated over the wetted length of the hull and corrected by an aspect-ratio correction developed by Pabst[5] to provide for a three-dimensional estimate of the total added mass in contact with the hull. This is the usual procedure used in seaplane impact theory and must be limited to the chines-dry impact of a constant deadrise hull.

More comprehensive impact theories dealing with heavily loaded, high length-beam ratio warped hulls were being developed for both smooth and rough water impact conditions when water-based aircraft research was essentially terminated. This new approach, which consists in exploiting the fact that planing is a particular case of impact, would have been of particular advantage to the planing hull. It can be applied to any hull shape for which planing data are available whether or not the chines are immersed and is not limited to prismatic surfaces. Steiner[7] used this approach to obtain a correlation between planing data and one of the empirico-theoretical virtual mass expressions using limited data mostly confined to the chines dry condition. Brown[8] and Smiley[9,10,11,12] exploit, to varying degrees, the concept that impact characteristics may be predicted from planing data. In both cases, the basic equations of motion governing the smooth water impact of a hull are formulated, integrated, and adapted to the prediction of smooth water impact loads and motions from planing equations. Since this work was carried out prior to the development of modern high speed computers, the analytical solutions are dependent

upon the application of special tabulated mathematical functions which
make the use of the computational procedure extremely tedious. This
method for impact calculations should be reactivated and extended to
the case of planing hull operation in waves. This extension was not
possible within the limited scope of the present study.

Analytical studies of the impact process establish the form of
relation between the impact force; the mass of the planing hull and
its geometry; and the relative approach conditions between hull and
wave; i.e., hull trim, hull velocity (horizontal and vertical components),
position in wave. These approach conditions are statistically related
and can only be determined from analysis of operational experiences.
At the present time, there is insufficient information to describe
realistic combinations of approach parameters to be used with impact
theory. These operational conditions require much further study.

ENGINEERING APPROXIMATION OF MAXIMUM ACCELERATIONS

The actual case of a planing craft operating in an irregular sea
state is a most difficult problem for precise analysis. As previously
noted, the basic impact theory requires further development; and among
the unknown, moreover, are the hull trim and velocities at the time of
impact and the geometry and relative position of the local wave surface
against which the hull impacts. In recent years, however, a moderate
amount of experimental data has been collected on the behavior of
planing hulls in waves. One of the more complete works is a report
by Chey[13] on model tests of a series of six patrol boats in smooth
and rough water. In that report, numerous plots of angular and
center-of-gravity accelerations are presented for round and hard chine
hulls in several irregular seas. It was believed that, by a
combination of present understanding of the fundamentals of impact
theory, full scale and model test observations of planing hulls in
waves, and a judicious set of approximations, an engineering procedure
for estimating maximum accelerations on planing hulls could be estab-
lished to at least be applicable within the range of available experi-
mental data. Accordingly, the following assumptions and approximations
have been made to represent the impact process and the hull-wave
contact conditions at the time of maximum hull acceleration.

A) Hydrodynamic Representation of the Impact Process

1) The planing hull is subjected to both dynamic and buoyant pressures during the planing and impact process. In steady planing, the dynamic lift (L_D) and the buoyant lift (L_B) can be obtained from planing lift equations such as given by Savitsky[14].

2) For a given trim angle, the dynamic pressures are taken to be proportional to the square of the velocity, $\dot{z}$, normal to the keel of the body relative to the adjacent fluid. This assumption is similar to that made by Smiley[9] and Brown[8] where hydrodynamic impact and planing are shown to be related. Then, $\dot{z}$ is equal to the sum of the normal component of the hull's vertical velocity $(\dot{z})$, the normal component of the hull's horizontal velocity $\dot{x}$, and the normal component of the vertical velocity of the wave $(\dot{h})$. This relationship can be written as:

$$\dot{z} = \dot{x} \sin\tau + \dot{y} \cos\tau + \dot{h} \cos\tau$$

where τ is the hull trim relative to level water.

3) All other conditions being equal, the hydrodynamic lift (L_D) is equal to the product of the average bottom pressure and the wetted bottom area. The wetted area is proportional to the mean wetted length (ℓ). Actually, as can be seen from Figure 10 of Ref. 14, a linear relation between planing lift and mean wetted length-beam ratio is realistic for the range of speed coefficients $(2.0 \leq C_V \leq 6.0)$ and mean wetted length-beam ratios $(1.5 \leq \lambda \leq 4.0)$ typical for planing hulls. Thus

$$L_D \approx (\dot{z})^2 (\ell)$$

4) For pure planing in smooth water (subscript o), the vertical velocity of the craft $(\dot{y}_o)$ and the velocity of the water $(\dot{h}_o)$ are both zero. The trim (τ_o) and corresponding effective wetted length (ℓ_o) are functions of the basic characteristics of the craft (beam, weight, center of gravity location, deadrise, and speed). Thus

$$\dot{z}_o = \dot{x} \sin\tau_o$$
$$\tau_o = f(b, \Delta, LCG, \beta, \dot{x})$$
$$\ell_o = f(b, \Delta, LCG, \beta, \dot{x})$$

The smooth water equilibrium condition shown in Figure 1 can be
evolved by applying the procedures of Ref. 14.

B) Relative Hull-Wave Contact Conditions at Time of Maximum Hull
   Acceleration (Figure 2)

1) In rough water (subscript max.) the maximum hydrodynamic
lift $(L_{D_{max}})$ occurs in head seas at the time of maximum chine immersion
(ℓ_{max}) and at the time when the vertical velocity $(\dot{y}_{max})$ of the hull
is essentially zero.

2) Observations of full-scale and model planing craft in waves
indicate that, at maximum acceleration, the mid-length of the craft
encounters the mid-flank of an oncoming wave and there is an increase
in the trim of the craft (τ_{max}) to equal the maximum slope (φ_{max}) of
the wave.

3) The length of the wave in contact with the hull is assumed
to move vertically with maximum wave orbital velocity, that is:

$$\dot{h}_{max} = \frac{\pi H_w}{T_w}$$

where T_w = wave period

H_w = wave height

Combining conditions (1), (2) and (3) above, the maximum velocity
normal to the full keel and the time of maximum acceleration in a wave
is given by

$$\dot{z}_{max} = \dot{x} \sin\tau_{max} + \dot{h}_{max} \cos\tau_{max}$$

where

$$\tau_{max} = \varphi_{max} \text{ or } \tau_0 \text{ (whichever is larger)}$$

$$\tan\varphi_{max} = \frac{\pi H_w}{\ell_w}$$

$$\dot{h}_{max} = \frac{\pi H_w}{T_w}$$

and

$$\cos\tau_{max} \approx 1$$

In these expressions, ℓ_w, H_w. and φ_{max} are the wave length, height
and maximum slope respectively. For irregular head seas, Table I can
be used to define these quantities as a function of wind speed or sea
state.

4) Relative to the magnitude of the hull wetted length and the time of maximum acceleration, it is assumed that for the case when (ℓ_w) is large relative to the hull length, the maximum effective wetted hull length (ℓ_{max}) is equal to the projected chine length (ℓ_c) as shown in Figure 2. In relatively shorter waves, the forebody of the craft extends beyond the wave crest and the maximum effective length is reduced to $(\ell_c/2 + \ell_w/8)$ or $3\ell_w/8$. Thus:

$$\ell_{max} = \ell_c \text{ or } (\frac{\ell_c}{2} + \frac{\ell_w}{8}) \text{ or } \frac{3}{8} \ell_w \text{ (whichever is smallest)}$$

C) Maximum Accelerations During Hull Impact in Waves

1) The ratio of maximum dynamic lift in rough water to the hydrodynamic lift during smooth water planing can be expressed

$$\frac{L_{D_{max}}}{L_{D_o}} = (\frac{\dot{z}_{max}}{\dot{z}_o})^2 \ (\frac{\ell_{max}}{\ell_o}) = (\frac{\dot{x} \sin\tau_{max} + \dot{h}_{max}}{\dot{x} \sin\tau_o})^2 \ (\frac{\ell_{max}}{\ell_o})$$

2) The ratio of maximum buoyant lift in rough water impact to buoyant lift during smooth water planing is taken to be

$$\frac{L_{B_{max}}}{L_{B_o}} = \frac{\ell_{max}}{\ell_o}$$

3) Using the basic characteristics of the craft (beam, weight, center of gravity location, deadrise, and speed), Ref. 14 can be used to calculate the dynamic lift (L_{D_o}) and the buoyant lift (L_{B_o}) during smooth water planing. Then

$$L_{D_o} = f(b, \Delta, LCG, \beta, \dot{x})$$
$$L_{B_o} = \Delta - L_{D_o}$$

4) Applying conditions (1), (2) and (3) above, the maximum total lift in rough water (L_{max}) can be computed:

$$L_{max} = L_{D_o} (\frac{L_{D_{max}}}{L_{D_o}}) + L_{B_o} (\frac{L_{B_{max}}}{L_{B_o}})$$

and the maximum center of gravity acceleration $(\ddot{y}_{CG_{max}})$ is

$$\ddot{Y}_{CG_{max}} = \frac{L_{max}}{\Delta} \; g$$

The corresponding load factor is

$$n_{CG_{max}} = \frac{\ddot{Y}_{CG_{max}}}{g} - 1$$

5) In rough water, it is assumed that the maximum total lift (L_{max}) acts at the centroid (LCF) of the chine planform area. Thus, the maximum applied pitching moment about the center of gravity can be written

$$M_{max} = L_{max}(LCF - LCG)$$

6) The mass moment of inertia (I) of the craft about its center of gravity is approximately

$$I = (.25 \; \ell_c)^2 \frac{\Delta}{g}$$

Thus, the maximum angular acceleration $(\ddot{\theta}_{max})$ is

$$\ddot{\theta}_{max} = \frac{M_{max}}{I}$$

and the associated linear acceleration $(\ddot{y}_\theta)$ at any distance (a) from the center of gravity is

$$\ddot{y}_\theta = \ddot{\theta}_{max}a$$

and the corresponding incremental load factor at any distance, a, from the center of gravity is then

$$n_{max} = \frac{\ddot{y}_\theta}{g} + \frac{\ddot{Y}_{CG_{max}}}{g} - 1$$

D) Summary of Engineering Procedure for Estimating Maximum Accelerations

1) Given:

Planing craft characteristics

$\Delta, b, \ell_c, LCG, LCF, \beta, \dot{x}, I$

Wave characteristics

H_w, ℓ_w, T_w

2) Objective:

Estimate maximum center of gravity and angular accelerations.

3) Procedure:

$$L_{D_o} = f_1(\Delta, b, LCG, B, \dot{x}) \qquad\qquad \text{from Ref. 14}$$

$$L_{B_o} = \Delta - L_{D_o}$$

$$\tau_o = f_2(\Delta, b, LCG, B, \dot{x}) \qquad\qquad \text{from Ref. 14}$$

$$\ell_o = f_3(\Delta, b, LCG, B, \dot{x}) \qquad\qquad \text{from Ref. 14}$$

$$\tan \varphi_{max} = \frac{\pi H_w}{\ell_w}$$

$$h_{max} = \frac{\pi H_w}{T_w}$$

$$\ell_{max} = \ell_c \text{ or } \left(\frac{\ell_c}{2} + \frac{\ell_w}{8}\right) \text{ or } \frac{3\ell_w}{8} \quad \text{whichever is smallest}$$

$$\tau_{max} = \varphi_{max} \text{ or } \tau_o \qquad \text{whichever is largest}$$

$$L_{D_{max}} = L_{D_o} \left[\frac{-\dot{x} \sin\tau_{max} + h_{max}}{\dot{x} \sin\tau_o}\right]^2 \left[\frac{\ell_{max}}{\ell_o}\right]$$

$$L_{B_{max}} = L_{B_o} \left[\frac{\ell_{max}}{\ell_o}\right]$$

$$L_{max} = L_{D_{max}} + L_{B_{max}}$$

$$\ddot{Y}_{CG_{max}} = \frac{L_{max}}{(\Delta/g)}$$

Also:

$$\ddot{M}_{max} = (LCF - LCG)L_{max}$$

$$I = (.25\ell_c)^2/C\Delta/g)$$

$$\ddot{\theta}_{max} = \frac{M_{max}}{I}$$

It may be that some of the previous assumptions which comprise this engineering procedure can be individually questioned. Nonetheless, it will be demonstrated that the synthesis of tnese elemental approximations does indeed compose a satisfactory engineering computational procedure which provides values of maximum accelerations that are in good agreement with model test results. This will be demonstrated in the following section of the report entitled "Verification". It is recommended that further study of the impact problem be pursued to establish a vigorously forward design procedure applicable for a wide range of impact conditions.

VERIFICATION

The proposed method has been employed to predict the center of gravity and angular accelerations of three hard chine hulls in a variety of irregular sea conditions. The calculated accelerations are compared with experimental model data reported by Chey[15].

Detailed calculations for the average and 1/10 highest accelerations at the center of gravity and bow are illustrated in Tables 2, 3 and 4 as a function of speed for head sea operation in sea state 3 and 5. The calculations are for Model 4928 and for sea state characteristics as described in Ref. 15. In particular, the hull and sea state properties are as follows:

Hull Characteristics (Model 4928, Ref. 15)

$\Delta = 55,000$ lbs.   (Full scale values)

$\ell_c = 42$ ft.

$b = 14$ ft.

$LCG/b = 1.29$

$\beta_{av} = 17.5^\circ$

$C_v = V/\sqrt{gb} = V/21.2$

$LCG = 18.05$ ft.

$LCF = 19.05$ ft.

$I = 200,000$ ft.-lbs.-sec.^{2}

$a = 13.45$ ft. (from LCG to bow accelerometer)

Sea State 5 Characteristics (as reported in Ref. 15)

$H_{av} = 5.5$ ft. (Full scale values)

$T_{av} = 6.0$ sec.

$\dot{h}_{av} = \dfrac{\pi H_{av}}{T_{av}} = 2.88$ ft.-sec.$^{-1}$

$\ell w_{av} = \dfrac{g T^2_{av}}{2\pi} = 184.5$ ft.

$\varphi_{av} = \tan^{-1} \dfrac{H_{av}\pi}{\ell w_{av}} = 5.4^\circ$

$H_{1/10} = 9.4$ ft.

$\mathring{h}_{1/10} = 4.92$ ft.-sec.$^{-1}$

$\varphi_{1/10} = 9.1$ degrees

Sea State 3 Characteristics (as reported in Ref. 15)

$H_{av} = 2.47$ ft.   (Full scale values)

$T_{av} = 4.5$ sec.

$\mathring{h}_{av} = 1.72$ ft.-sec.$^{-1}$

$\ell_w = 104$ ft.

$\varphi_{av} = 4.14^{\circ}$

$H_{1/10} = 4.42$ ft.

$\mathring{h}_{1/10} = 3.09$ ft.-sec.$^{-1}$

$\varphi_{1/10} = 7.63$ degrees

Table 2 presents the results of calculations for the smooth
water performance as a function of speed from 15 to 45 ft/sec. Pre-
sented in Table 2 are the equilibrium trim angle (τ_o); the equilibrium
mean wetted length-beam ratio (λ_o) and the dynamic (L_{D_o}) and buoyant
(L_{B_o}) components of planing lift force. Table 3 presents the details
of the computations and results for the center-of-gravity acceleration
(both average and 1/10 highest) as a function of speed for sea states
3 and 5. Table 4 considers the bow accelerations for similar test conditions.

Comparisons between computed and measured accelerations are
given in Figures 3 through 10. It can be seen that the agreement
between computed and measured accelerations is reasonably good--at
least for engineering design purposes. In general, the computed accel-
erations appear to be somewhat higher than measured values, especially
at speeds in excess of approximately 35 knots. Similar calculations
and comparisons have been made for hull forms 4929 $(\beta_{av} = 19^{\circ})$ and
2387 $(\beta_{av} = 19^{\circ})$ described in Ref. 15. The agreement between computed
and measured results is equally favorable; detailed comparisons are
therefore not presented in this report.

A brief study was made of the effects of trim change and loading change on the average center-of-gravity acceleration for Model 4928 planing at 30 knots in a sea state 5. It was found that a 50% increase in trim resulted in a 90% increase in acceleration while a 50% increase in loading resulted in a 25% decrease in acceleration. These results are qualitatively in agreement with the conclusions of Savitsky[16] and Fridsma[17], thus further confirming the applicability of the proposed engineering computational procedure.

CONCLUSIONS

General agreement between calculated and experimental results indicates that the proposed method for computing maximum accelerations of planing craft during rough water operation is realistic. Since the method is easy to apply and requires no knowledge of the detailed craft characteristics, this procedure should be particularly useful during preliminary design.

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WIND AND SEA SCALE FOR FULLY ARISEN SEA

Sea State [1]	Description [2]	Beaufort Wind Force	Description	Range (knots)	Wind Velocity Average (knots)	Wave Height — Significant (ft)	Wave Height — Average (ft)	Wave Height — Highest 1/10 (ft)	Significant Range of Periods (seconds)	Period of Max Energy of Spectrum T_{max}	$\bar{T}$ (Average Period)	Average Wave Length (feet)	Minimum Fetch (nautical miles)	Minimum Duration (hours)
0	Sea like a mirror.	0	Calm	Less than 1	0	0	0	0	–	–	–	–	–	–
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1-3	2	0.05	0.08	0.10	up to 1.2 sec	0.7	0.5	10 in.	5	18 min
1	Small wavelets, still short but more pronounced; crests have a glassy appearance, but do not break.	2	Light Breeze	4-6	5	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7-10	8.5	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hrs
2					10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
					12	1.4	2.2	2.8	1.8-7.0	4.6	3.4	40	16	3.8
3	Small waves, becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
					14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
					16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray).	5	Fresh Breeze	17-21	18	3.3	6.1	7.8	2.5-10.8	7.2	5.1	90	55	8.5
					19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
					20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
6					24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
					26	9.6	15	20	4.0-14.5	10.5	7.4	168	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
7					30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8-19.7	14.5	10.3	363	500	34
					37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2-20.8	15.4	10.7	392	600	38
					40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
					44	36	58	73	7-24.2	17.7	12.5	534	960	52
					46	40	64	81	7-25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole Gale [*]	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
					50	49	78	99	7.5-27	20.2	14.3	700	1420	69
					51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
9					52	54	87	110	8-28.5	21	14.8	750	1610	75
					54	59	95	121	8-29.5	21.4	15.4	810	1800	81
	Exceptionally high waves (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm [*]	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
					59.5	73	116	148	10-32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane [*]	64-71	>64	>80 [b]	>128 [b]	>154 [b]	10-(35)	(26)	(18)	~	~	~

Notes (right column):

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

a)A heavy box around this area means that the values tabulated are at the center of the Beaufort range.

b)For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

1)Encyclopedia of Nautical Knowledge, W.A. McEwen and A.H. Lewis, Cornell Maritime Press, Cambridge, Maryland, 1953, p. 483

2)Manual of Seamanship, Volume II, Admiralty, London, H.M. Stationery Office, 1952, pp. 717-717.

3)Practical Methods for observing and forecasting Ocean Waves, Pierson, Neumann, James, N.Y. Univ, College of Engin. 1953.

TABLE 11. CALCULATIONS FOR SMOOTH-WATER PERFORMANCE
(Model 4928, Ref. 15)

Δ	b		v	$\dot{x}$	q	Cl_b	$\dfrac{LCG}{b}$	c_v	λ_o	$\dfrac{Cl_o}{\tau_o^{1.1}}$	β	Cl_c	$\tau_o^{1.1}$	τ_o	Cl_{o_o}	Cl_{b_o}	L_o	L_{R_o}
55,000	14		15	25.4	645	0.435	1.29	1.2	2.9	0.075	17.5	0.51	6.8	5.7	0.139	0.105	13,300	41,700
			20	33.8	1,140	0.245		1.59	2.4	0.038		0.30	7.9	6.55	0.147	0.11	24,600	30,400
			25	42.25	1,785	0.157		1.98	2.15	0.027		0.20	7.41	6.2	0.13	0.10	35,000	20,000
			30	50.7	2,570	0.109		2.39	1.95	0.022		0.14	6.36	5.36	0.1065	0.08	40,300	14,700
			35	59.2	3,500	0.08		2.79	1.90	0.02		0.11	5.5	4.71	0.091	0.064	43,900	11,100
			40	67.6	4,570	0.0613		3.19	1.85	0.019		0.087	4.57	3.98	0.0737	0.049	44,000	11,000
			45	76	5,780	0.0486		3.59	1.80	0.018		0.074	4.11	3.61	0.0664	0.042	47,500	7,500
			15	25.4													13,300	41,700
			20	33.8													24,600	30,400
			25	42.25													35,000	20,000
			30	50.7													40,300	14,700
			35	59.2													43,900	11,100
			40	67.6													44,000	11,000
			45	76													47,500	7,500
			15	25.4													13,300	41,700
			20	33.8													24,600	30,400
			25	42.25													35,000	20,000
			30	50.7													40,300	14,700
			35	59.2													43,900	11,100
			40	67.6													44,000	11,000
			45	76													47,500	7,500
			15	25.4													13,300	41,700
			20	33.8													24,600	30,400
			25	42.25													35,000	20,000
			30	50.7													40,300	14,700
			35	59.2													43,900	11,100
			40	67.6													44,000	11,000
			45	76													47,500	7,500

TABLE III. CALCULATIONS FOR CG ACCELERATIONS
(Model 4928, Ref. 15)

v	$\ddot{x}\sin\tau_o$	ϕ_{max}	$\tau_{max}=\tau_o$ or ϕ_{max}	$\ddot{x}\sin\tau_{max}$	h_{max}	$\ddot{x}\sin\tau_{max}+\ddot{h}$	$\dfrac{\ddot{h}+\ddot{x}\sin\tau_{max}}{\ddot{x}\sin\tau_o}$	$\left(\dfrac{\ddot{h}+\ddot{x}\sin\tau_{max}}{\ddot{x}\sin\tau_o}\right)^2=k_1$	l_{max}	$\dfrac{l_{max}}{\ddot{y}_o b}=k_2$	$k_1k_2l_o=\ddot{l}_{b_o max}$	$k_2l_{b_o}=\ddot{l}_{b max}$	$\ddot{l}_{b_o max}+\ddot{l}_{b max}=\ddot{l}_{max}$	$l_{max}=\dfrac{\ddot{y}_{CG}}{g}=\Delta$	$\dfrac{\ddot{y}_{CG}}{g}-1$	Notes
15	2.52	5.4	5.7	2.52	2.88	5.4	2.14	4.58	42	1.035	63,000	44,200	107,200	1.95	0.95	Sea State 5 / Head Seas / Average
20	3.85		6.55	3.85		6.73	1.75	3.06		1.25	94,000	38,000	132,000	2.40	1.40	
25	4.56		6.2	4.56		7.44	1.63	2.66		1.395	130,000	27,900	157,900	2.87	1.87	
30	4.74		5.4	5.56		7.64	1.61	2.59		1.54	161,000	22,600	183,600	3.34	2.37	
35	4.85		5.4	6.35		8.44	1.74	3.02		1.58	210,000	17,500	227,500	4.14	3.14	
40	4.69		5.4	7.14		9.23	1.97	3.80		1.62	276,000	17,800	293,800	5.34	4.34	
45	4.78					10.02	2.09	4.37		1.67	346,000	12,500	358,500	6.52	5.52	
15	2.52	9.1	9.1	4.00	4.92	8.92	3.54	12.5	42	1.035	172,000	44,200	216,200	3.94	2.94	Sea State 5 / Head Seas / Avg. 1/10 Highest
20	3.85			5.35		10.27	2.66	7.08		1.25	217,000	38,000	255,000	4.64	3.64	
25	4.56			6.68		11.60	2.54	6.45		1.395	315,000	27,900	342,900	6.24	5.24	
30	4.74			8.00		12.92	2.73	7.45		1.54	462,000	22,600	484,600	8.80	7.80	
35	4.85			9.35		14.27	2.94	8.65		1.58	600,000	17,500	617,500	11.25	10.25	
40	4.69			10.7		15.62	3.33	11.1		1.62	790,000	17,800	807,800	14.70	13.70	
45	4.78			12		16.92	3.54	12.5		1.67	992,000	12,500	1,004,500	18.25	17.25	
15	2.52	4.14	5.7	2.52	1.72	4.24	1.68	2.82	34	0.838	31,400	34,900	66,300	1.205	0.205	Sea State 3 / Head Seas / Average
20	3.85		6.55	3.85		5.57	1.45	2.10		1.01	52,100	30,700	82,800	1.505	0.505	
25	4.56		6.2	4.56		6.28	1.38	1.90		1.13	75,200	22,600	57,800	1.78	0.78	
30	4.74		5.36	4.74		6.46	1.36	1.65		1.245	92,800	18,300	111,100	2.02	1.02	
35	4.85		4.71	4.85		6.57	1.35	1.82		1.28	102,500	14,200	116,700	2.12	1.12	
40	4.69		4.14	4.88		6.60	1.41	1.99		1.31	115,000	14,400	129,400	2.35	1.35	
45	4.78		4.14	5.48		7.20	1.505	2.26		1.35	145,000	10,000	155,100	2.82	1.82	
15	2.52	7.63	7.63	3.38	3.09	6.47	2.57	6.60	34	0.838	73,500	34,900	108,400	1.97	0.97	Sea State 3 / Head Seas / Avg. 1/10 Highest
20	3.85			4.50		7.59	1.97	3.88		1.01	96,500	30,700	127,200	2.31	1.31	
25	4.56			5.62		8.71	1.91	3.54		1.13	140,000	22,600	162,600	2.96	1.96	
30	4.74			6.75		9.84	2.07	4.28		1.245	215,000	18,300	233,300	4.24	3.24	
35	4.85			7.86		10.95	2.26	5.1		1.28	286,000	14,200	300,200	5.46	4.46	
40	4.69			9.00		12.09	2.58	6.65		1.31	383,000	14,400	397,400	7.22	6.22	
45	4.78			10.1		13.19	2.76	7.62		1.35	489,000	10,100	499,100	9.09	8.05	

TABLE IV. CALCULATIONS FOR BOW ACCELERATIONS
(Model 4928, Ref. 15)

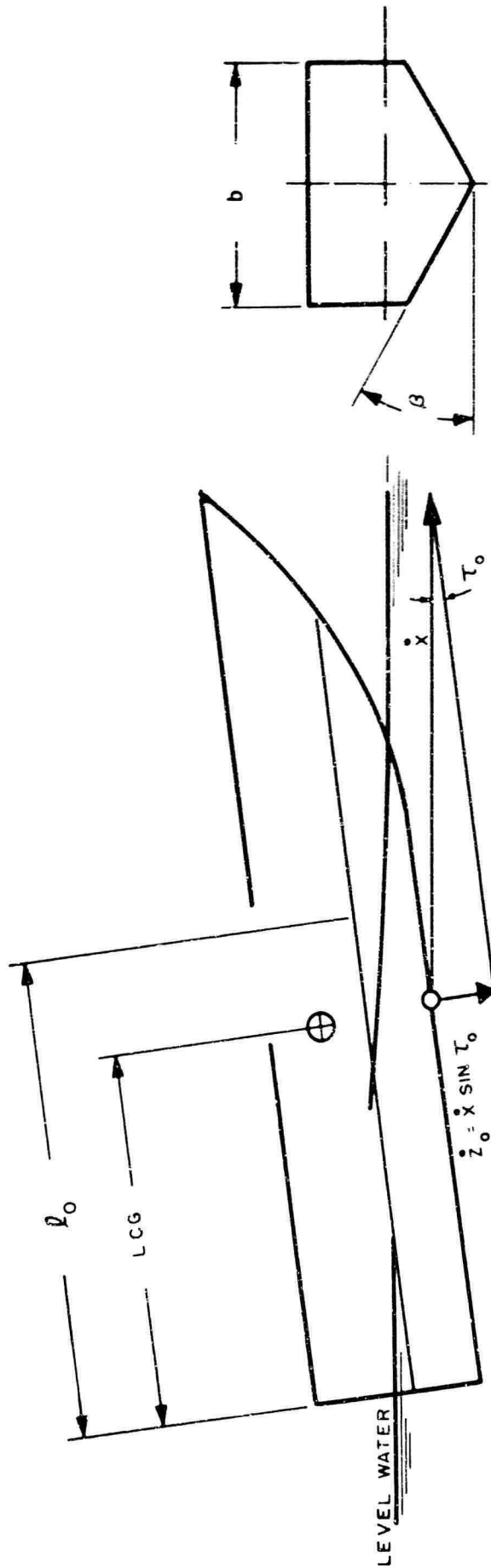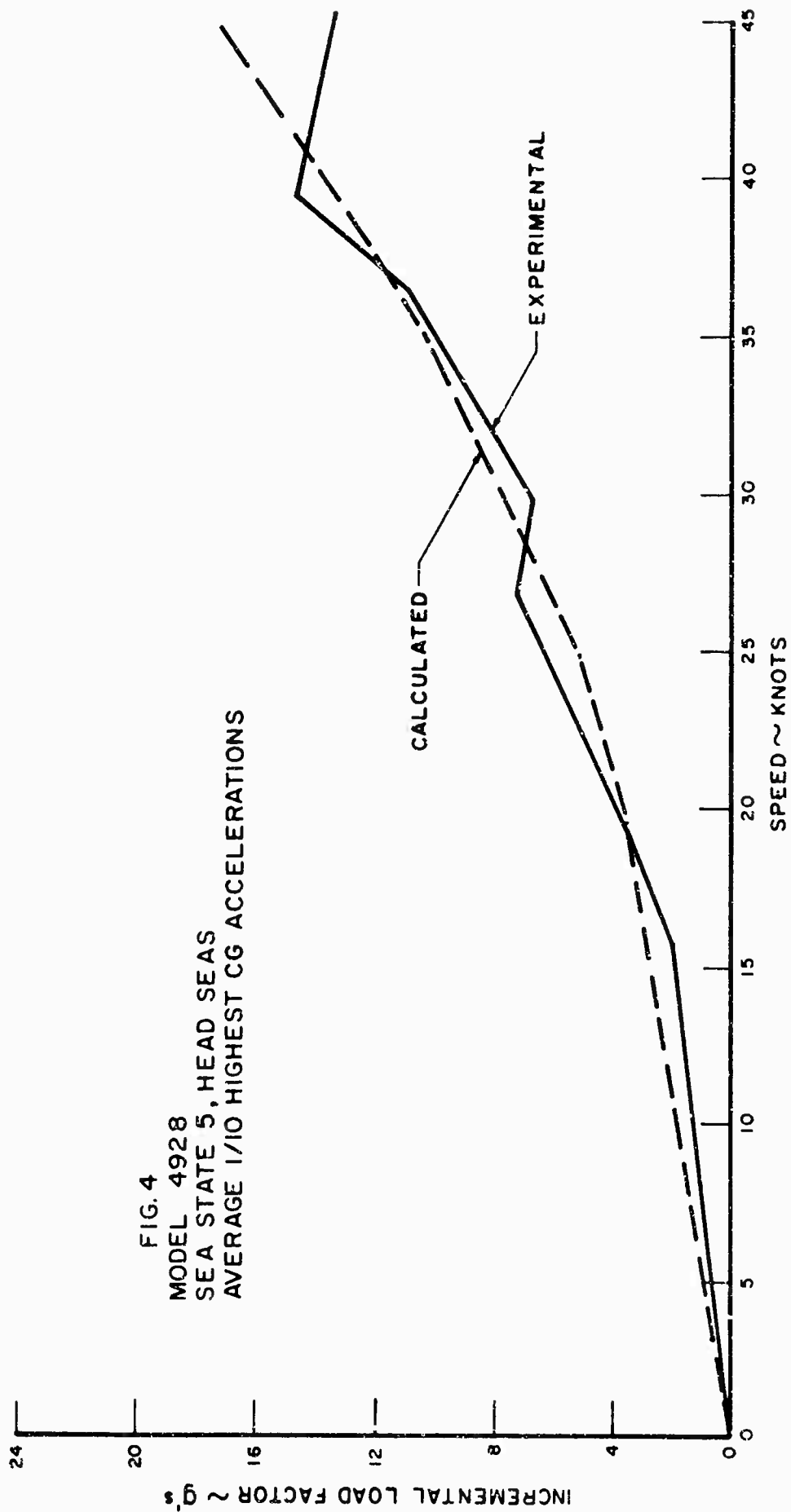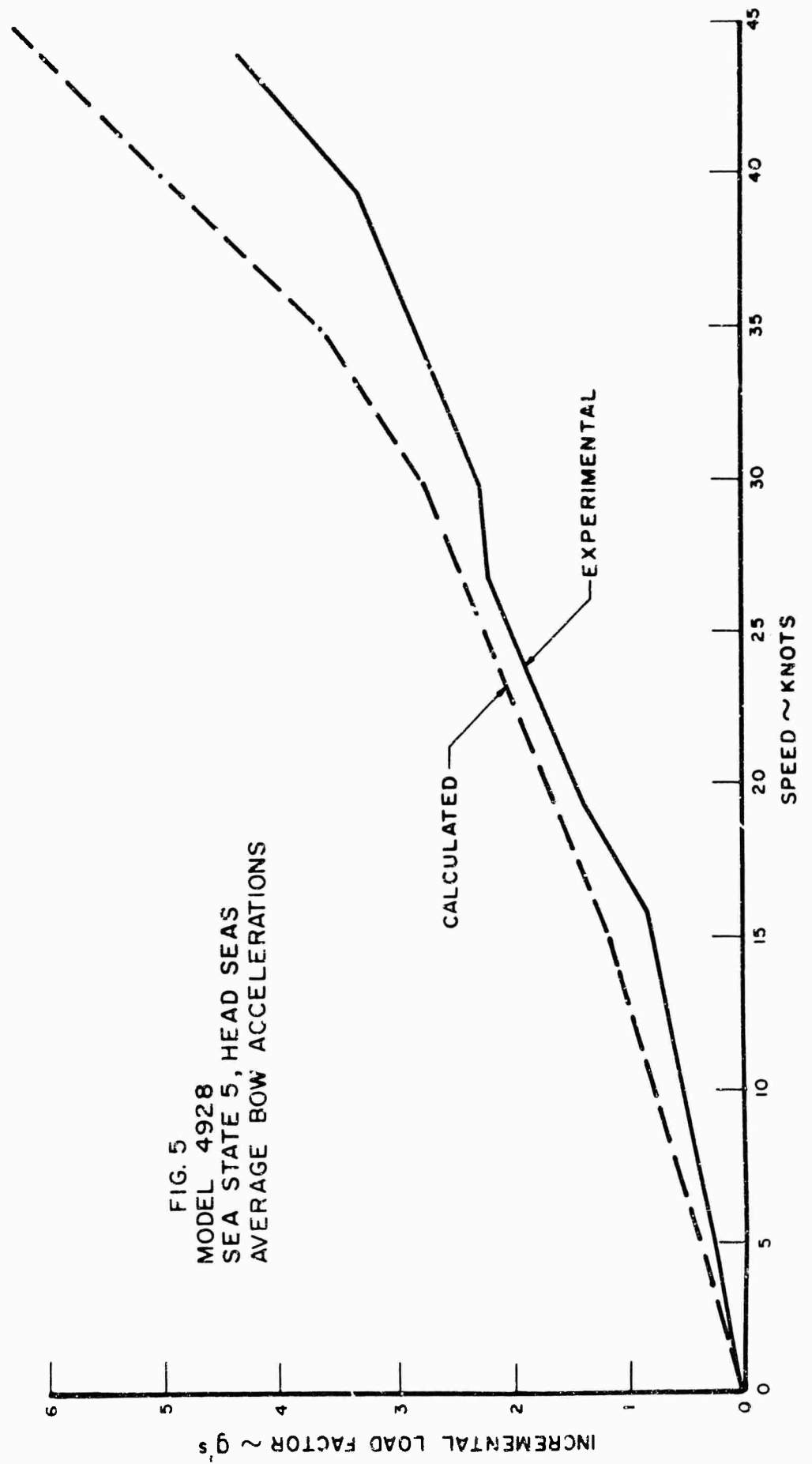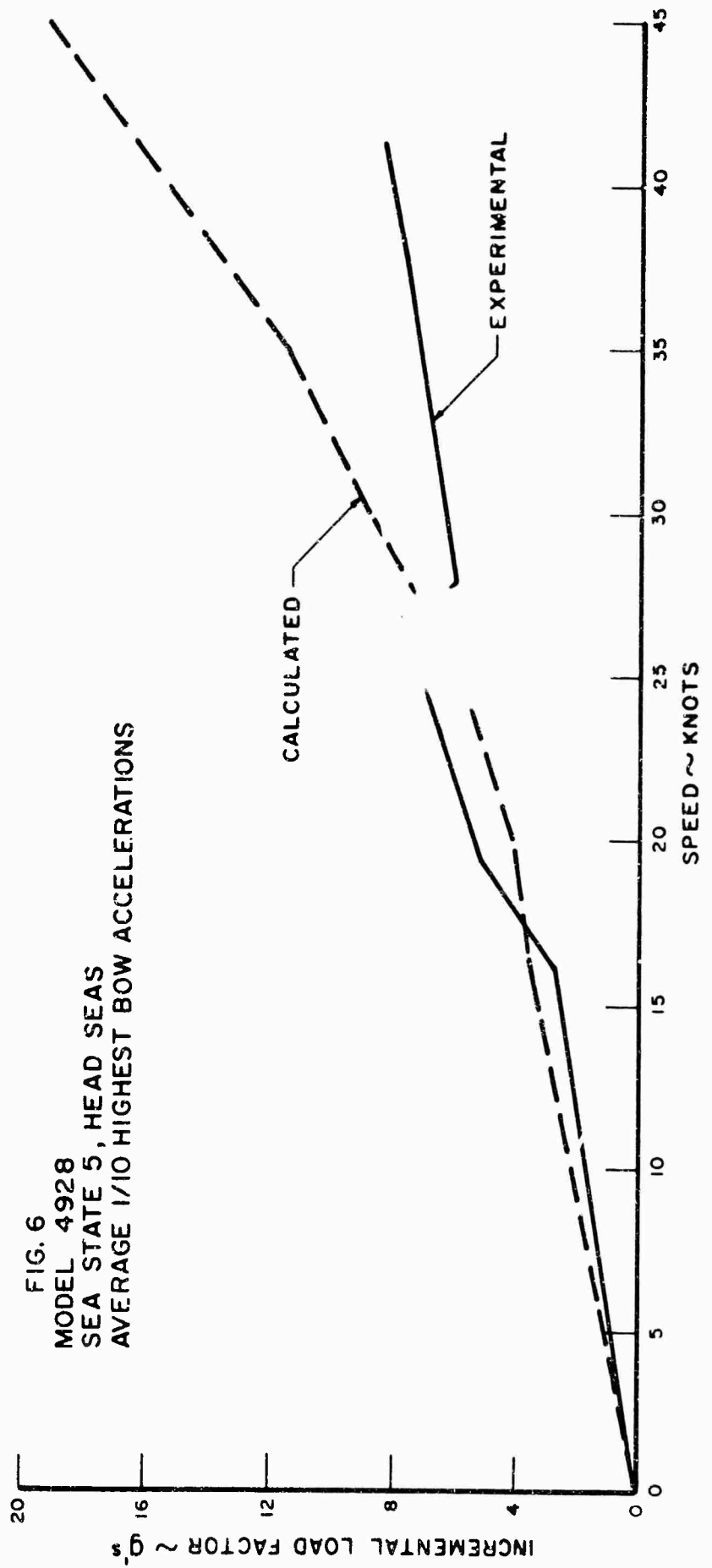| V	LCF	LCG	LCF-LCG	L_{max}	$(LCF-LCG)\,L_{max} = M_{max}$	I	$\ddot{\theta}_{max}$	θ	$\ddot{\theta}_{max}(g) = \dfrac{g}{\ddot{y}_g}$	$\dfrac{\ddot{y}_{cg}}{g} - 1$	$\dfrac{\ddot{\theta}}{g} \div \dfrac{\ddot{y}_{cg}}{g} - 1$	
15	19.05	18.05	1.00	107,200	107,200	200,000	0.536	13.45	0.224	0.95	1.174	
20				132,000	132,000		0.66		0.276	1.40	1.676	Sea State 5
25				157,900	157,900		0.79		0.33	1.87	2.20	Head Seas
30				183,600	183,600		0.916		0.383	2.37	2.753	Average
35				227,500	227,500		1.14		0.475	3.14	3.615	
40				293,800	293,800		1.47		0.613	4.34	4.953	
45				358,500	358,500		1.79		0.748	5.52	6.266	
15			1.00	216,200	216,200	200,000	1.08	13.45	0.451	2.94	3.391	
20				255,000	255,000		1.275		0.533	3.64	4.173	Sea State 5
25				324,900	324,900		1.625		0.679	5.24	5.919	Head Seas
30				484,600	484,600		2.42		1.02	7.80	8.82	Avg. 1/10 Highest
35				617,500	617,500		3.065		1.29	10.25	11.54	
40				807,800	807,800		4.04		1.69	13.70	15.39	
45				1,004,500	1,004,500		5.02		2.10	17.25	19.35	
15			1.00	66,300	66,300	200,000	0.332	13.45	0.138	0.205	0.343	
20				82,800	82,800		0.414		0.173	0.505	0.678	Sea State 3
25				97,800	97,800		0.489		0.204	0.78	0.984	Head Seas
30				111,100	111,100		0.555		0.232	1.02	1.252	Average
35				116,700	116,700		0.583		0.244	1.12	1.364	
40				129,400	129,400		0.647		0.270	1.35	1.62	
45				155,100	155,100		0.775		0.324	1.82	2.144	
15			1.00	108,400	108,400	200,000	0.542	13.45	0.226	0.97	1.196	
20				127,200	127,200		0.636		0.266	1.31	1.576	Sea State 3
25				162,600	162,600		0.813		0.339	1.96	2.299	Head Seas
30				233,300	233,300		1.166		0.486	3.24	3.726	Avg. 1/10 Highest
35				300,200	300,200		1.50		0.626	4.46	5.086	
40				397,400	397,400		1.985		0.83	6.22	7.05	
45				499,100	499,100		2.50		1.04	8.09	9.13	

FIG. I SMOOTH WATER PURE PLANING
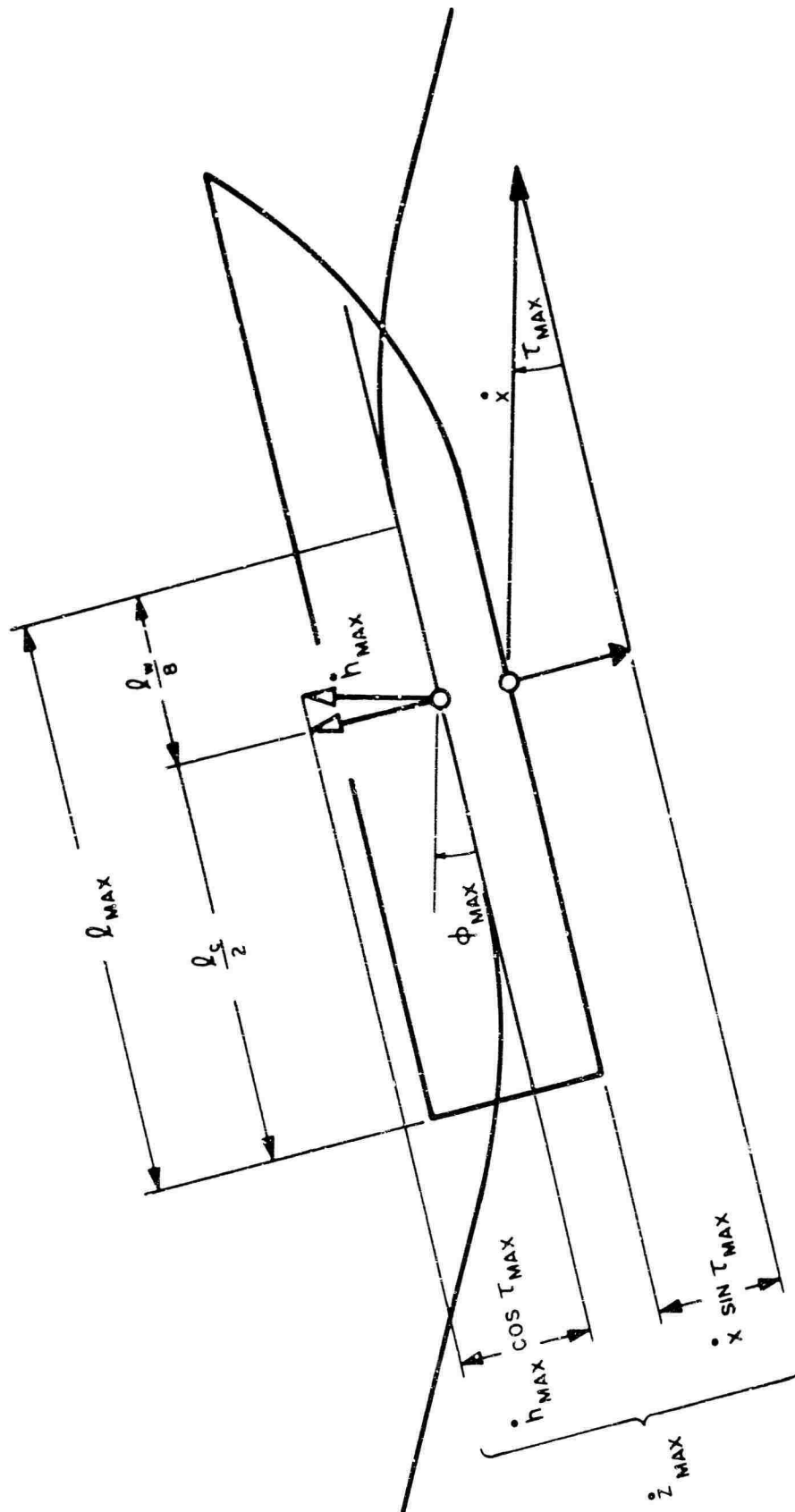
FIG.2 ROUGH WATER MAXIMUM LOAD CONDITION

FIG. 3
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE CG ACCELERATIONS

FIG. 4
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE 1/10 HIGHEST CG ACCELERATIONS

FIG. 5
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE BOW ACCELERATIONS

FIG. 6
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE 1/10 HIGHEST BOW ACCELERATIONS

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FIG. 7
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE CG ACCELERATIONS

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FIG. 8
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE BOW ACCELERATIONS

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FIG. 9
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE 1/10 HIGHEST CG ACCELERATIONS

FIG. 10
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE 1/10 HIGHEST CG ACCELERATIONS

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13. ABSTRACT

An engineering procedure is presented for estimating the maximum impact accelerations experienced by planing craft in irregular head seas. General agreement between calculated and model test results indicates that the proposed method is realistic. The procedure should be particularly useful during preliminary design.

DD FORM 1473 (PAGE 1)
1 NOV 65

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Planing Hulls						
Impact Accelerations						

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